International Journal of Industrial Electronics, Control and Optimization © 2021 IECO
Vol. 4, No. 1, pp. 59-65, Jan (2021)

# RF Power Harvester Using a Broadband Monopole Antenna and a Quad-Band Rectifier

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ABSTRACT

*An RF energy harvester (rectenna) consists of a broadband monopole antenna and a quad-band rectifying circuit is designed to harvest EM wave energy in the frequency range of 1.412 GHz to 8.56 GHz, which covers GSM-1800, LTE-band, WiMax, Wi-Fi, and WLAN. The initial component of the rectenna is an antenna that includes a semi-circular radiating patch with 8 circular stubs and a semicircle ground plane. The simulation results show the antenna has −10 dB impedance bandwidth at 7.148 GHz (from 1.412 GHz to 8.56 GHz). The second part of the rectenna is a rectifier circuit with a quad-band matching network for RF to DC conversion. The rectifier benefits from a two-stage Dickson rectifier using Schottky diodes. The RF-DC conversion efficiency and output DC voltage are simulated, and the maximum output voltage of the rectifier is 7.2 V with the optimum load resistance of* $R = 12\ k\Omega$ *and the peak conversion efficiency is 65.3%, when the input power of the rectifier is set -4 dBm at 1.71 GHz.*

**Article Info**

***Keywords:***
Broadband antenna, Quad-band Matching network, RF Energy Harvesting, Rectenna.

***Article History:***
**Received** 2020-06-05
**Accepted** 2020-08-20

## I. INTRODUCTION

The technology of power transmission and energy harvesting from radio frequency electromagnetic waves, to supply power to wireless electronic devices, is of interest [1-2]. This kind of energy sources can be employed to power wireless sensors and networks [3-4]. Fig. 1 shows the components of an RF energy harvesting system (Rectenna) including the receiving antenna, matching network, RF to DC rectifier circuits, and a load [5].

The antenna can operate in one or more frequency bands with linear or circular polarization. The task of the antenna is to harvest the electromagnetic wave energy available in the environment. In the next step, the harvested wave is rectified. The matching network is a resonant circuit operating at the frequency band, and its purpose is to maximize the transmission power between the antenna and the RF to DC converter. The RF to DC converter comprises at least one rectifier circuit to transform the RF power to DC power. The output voltage of this circuit can be stored in a battery or used directly to power a load. The RF conversion efficiency of the receiver depends on the accuracy of the impedance matching between the antenna and the transducer and the power efficiency of the transducer. Also, the antenna bandwidth plays an important role on the efficiency of the system to harvest environmental RF energy.

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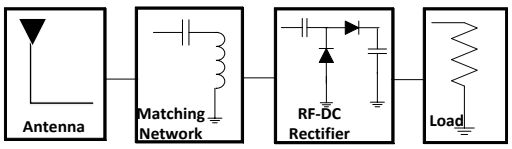



**Fig 1**. The block diagram of an energy harvesting system

In recent years, various broadband Rectenna (antenna integrated with rectifier circuit) have been introduced for the RF energy harvesting applications. Several broadband antennas are presented in [6-15], and different rectifiers are presented in [6-21]. In [6], the simulated impedance bandwidth of the antenna is 4.39 GHz (0.81 GHz-5.2 GHz). In [7], the impedance bandwidth of the antenna is 1.2 GHz (2.1 GHz-3.2 GHz), and in [10], the impedance bandwidth is 0.7 GHz (from 2 GHz to 2.7 GHz). Besides, several single band rectifiers [16], dual-band rectifiers [17,18], and multiband rectifiers [19-21] have been proposed employing different technologies. The advantages of the broadband antenna are more energy harvesting power than a single band [22], dual-band [23], or triple-band antennas [24] as well as energy harvesting from several bands.

This paper describes a new RF energy harvester (Rectenna) consists of a broadband monopole antenna and a quad-band rectifying circuit. The following sections describe the system. Part II describes the configuration and simulation results of the broadband antenna. Part III interprets the design and simulation results of the rectifier circuit and the matching network. Conclusions are presented in part IV.

## II. BROADBAND ANTENNA STRUCTURE

The planar antenna is implemented on RT/duroid 5880 substrate with a thickness of 1.57 mm, having a dielectric constant of 2.2 and a loss tangent of 0.0009. It is designed employing HFSS software. The dimension of the dielectric substrate is 43×44 mm2. The main radiating part of the antenna is a semicircle patch. So this structure can be considered as a circular patch, and its dimensions can be calculated using the formulations given in [25].

The antenna design process is shown in Fig. 2. The initial structure consists of a semicircular patch on the substrate with a 50 Ω feed line and a rectangular ground plate with dimensions 14×44 $mm^2$ at the bottom of the substrate. In the first structure, the simulation result (Fig. 3) shows that the impedance bandwidth of the antenna is 4.6 GHz (from 1.4 GHz to 6 GHz). In the second structure, by loading the radiating patch with 8 circular stubs with radius $R_C = 2\,mm$, the impedance bandwidth of the antenna is increased to 6.988 GHz (from 1.412 GHz to 8.4 GHz) (Fig. 3). The circular stubs produce inductive reactance and remove the capacitive reactance in the radiating patch, which in turn creates the wideband characteristic.

As shown in Fig. 2, for Structure 3, the ground plane is amended to a semicircle to produce a better matching as well as multiple resonating bands. Hence, the current which flows in the semicircular ground plane, has a longer path in comparison with current in a rectangular ground plane, resulting more resonating bands with improving return loss. As a result, the bandwidth of the antenna increased to 7.148 GHz (from 1.412 GHz to 8.56 GHz). Fig. 3 compares the reflection coefficients for the structures described in Fig. 2. Fig. 4 illustrates the smith chart with and without the 8 circular stubs. It is clear that by adding more stubs, the inductive property of the antenna can be increased.

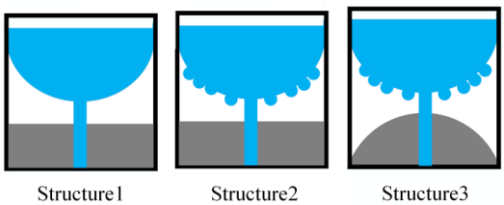



**Fig 2.** The shape of the antenna at different stages of design process

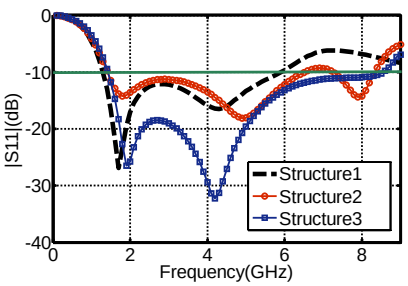
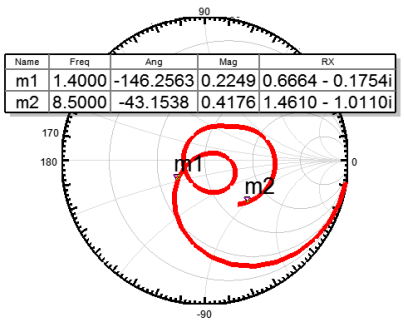
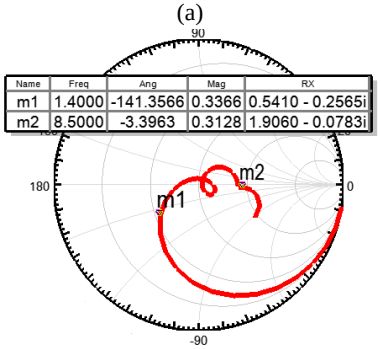



**Fig 3.** Influence of the rectangular ground, circular stubs, and semicircle ground on the reflection coefficient of the antenna.



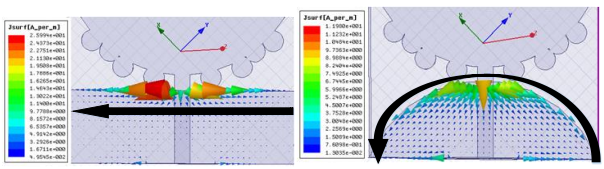

(a)




(b)

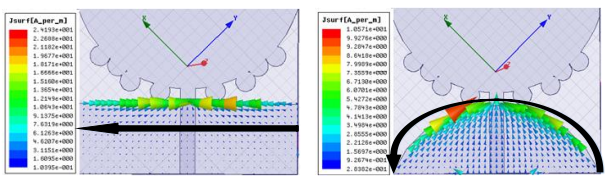
**Fig 4**. Smith chart (a) before adding subs (b) after adding stubs

Fig. 5 and Fig. 6 indicate the surface current distribution of the antenna on the rectangular ground plane and the semicircular ground plane at 1.9 GHz and 4.2 GHz, respectively. It can be observed that the intensity of the current flow in the semicircular ground is much higher than the rectangular ground at the desired frequency. Also, the dimension of the current path is indicated by the black arrows. This verifies that the length of the current path in a semicircular ground is much greater than a rectangular ground at selected frequencies. Therefore, this causes the new antenna to generate multiple resonance in different bands, which gives much higher bandwidth.



(a) (b)

**Fig 5**. Surface current distribution at 1.9 GHz, (a) on a rectangular ground plate (b) on a semicircular ground plane



(a) (b)

**Fig 6**. Surface current distribution at 4.2 GHz, (a) on a rectangular ground plate (b) on a semicircular ground plane

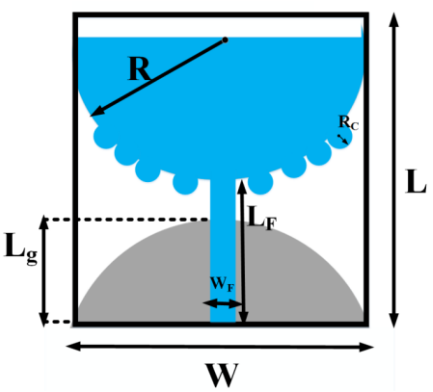



**Fig 7**. Configuration of the proposed antenna. Physical size of the antenna is equal to:

$L = 43 \ \ mm,\ W = 44 \ \ mm,\ R = 22 \ \ mm,\ W_F = 3 \ \ mm,$

$L_F = 18 \ \ mm, \ \ R_C = 2 \ \ mm\ ,\ L_g = 15 \ \ mm\ .$

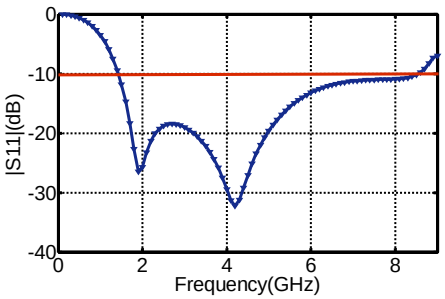



**Fig 8.** The simulated reflection coefficient ($|S_{11}|$) of the suggested antenna

Considering the effect of the ground plane and circular stubs of the behavior of the patch antenna, the final design of the antenna for the power harvesting system has been proposed. Fig. 7 demonstrates the finalized structure of the monopole antenna indicating the optimized values of the parameters and patch sizes. The simulated reflection coefficient ($|S_{11}|$) of the antenna is demonstrated in Fig. 8, signifying the antenna has −10 dB impedance bandwidth of 7.148 GHz (From 1.412 GHz to 8.56 GHz).

Fig. 9 illustrates the simulated far-field radiation patterns in the x–z plane and y-z plane at frequencies of 1.8, 2.1, 2.4, 3.6, and 5.8 GHz, respectively. The radiation pattern of the proposed antenna is Omni-directional in both the vertical and the azimuthal planes. Thus, this achieved characteristic makes the new antenna suitable for RF energy harvesting applications.

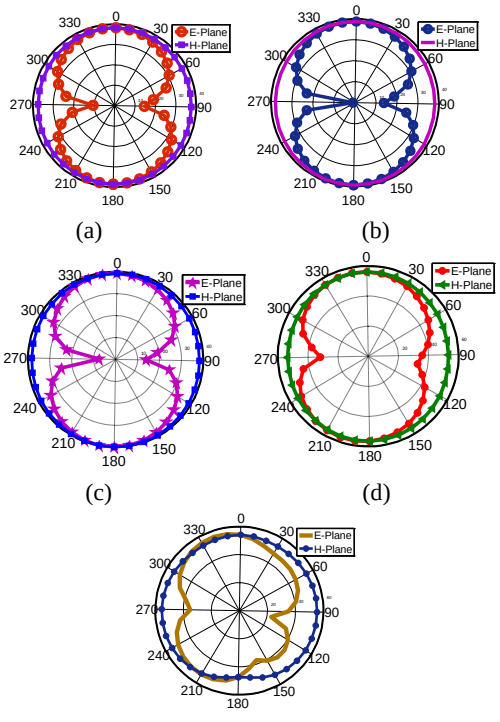



**Fig. 9.** Simulated radiation pattern of the proposed antenna for *x-z* plane and x-y plane at (a) 1.8, (b) 2.1, (c) 2.4 (d) 3.6 and (e) 5.8 GHz.

## III. MULTI-BAND RECTIFIER STRUCTURE

The design and simulation of a quad-band rectifier are performed on an RT/duroid 5880 substrate with a thickness of 1.57 mm, a dielectric constant of 2.2, and a loss tangent of 0.0009. The design of the rectifier circuits is demonstrated in Fig. 10 and is performed by the Advanced Design System (ADS) software.

The RF signal is rectified by a two-stage Dickson rectifier using the SMS7630 Schottky diode [21]. This type of diode is chosen for the rectifier due to its low biasing voltage requirement for a weak input signal (forward bias voltage: 60–120 mV @ 0.1 mA). To simulate SMS-7630 diode, the SPICE model parameters are utilized from [26]. A resonant impedance matching network at four frequencies is designed to match the antenna and rectifier circuit and thus achieve the maximum output power. The matching network is described in Fig. 10, which include several inductive-capacitive resonator circuit. The proposed quad-band circuit is designed at frequencies 1.71, 2.4, 3.6, and 6.1 GHz. The resonant frequency of the proposed circuit is $\omega_r$. The physical length $(l)$ of the short-circuited stubs is calculated from the following formulas [21]:

$$\omega_r = \frac{1}{\sqrt{LC}} \tag{1}$$

$$\frac{\omega_r L}{2} = Z_0 \tan(\frac{\beta l}{2}) \tag{2}$$

In equation (1), the series capacitance and inductance are denoted by L and C. In equation (2), $\beta l$ expresses the electrical length of the short-circuited stub and $Z_0$ represents the characteristic impedance of the transmission line (TL). The calculated sizes of TL components of the circuit are indicated in Fig. 10.

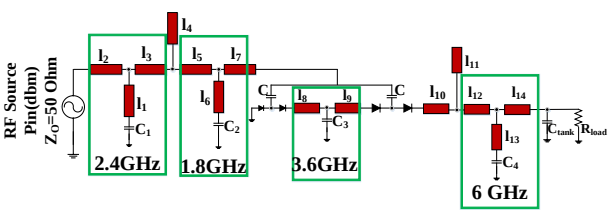



**Fig 10**. Configuration of the proposed quad-band rectifier with a matching network. Physical size of the antenna is equal to:

$l_1 = 14.3\ mm$, $l_2 = 3\ mm$, $l_3 = 2.8\ mm$, $l_4 = 19.8\ mm$, $l_5 = 0.66\ mm$, $l_6 = 23\ mm$, $l_7 = 14.3\ mm$ $l_8 = 13.5\ mm$, $l_9 = 13.5\ mm$, $l_{10} = 5.8\ mm$, $l_{11} = 10\ mm$, $l_{12} = 5.8\ mm$, $l_{13} = 4.25\ mm$, $l_{14} = 1.3\ mm$, $W\ for\ all\ transmission\ lines\ is\ 2.24\ mm$.

The rectifier was simulated by the Large Signal S-Parameter (LSSP) simulator of ADS software. The simulated reflection coefficient versus frequency of the quad-band rectifier at the input power of 0 dBm is plotted in Fig. 11. The circuit resonates at frequencies of 1.71 GHz, 2.43 GHz, 3.68 GHz, and 6.1 GHz. To achieve the output DC voltage and RF-DC conversion efficiency diagrams in terms of various input power levels (from -30 dBm to +30 dBm), the rectifier is simulated using the Harmonic Balance (HB) simulator in ADS, which indicates that, the output voltage is obtained at the optimum load resistance of 12 kΩ.

Equation (3) is used to compute the RF-DC conversion efficiency [12]. As specified in equation (3), $P_{input}$ is the incident RF power while $P_0$ is the output DC power. The output DC voltage and load resistance are denoted by $V_0(DC)$ and $R_{Load}$, respectively.

$$Efficiency\ (\%) = \frac{P_o(DC)}{P_{input}} \times 100 = \frac{V_O^{\ 2}(DC)}{R_{Load}} \times \frac{1}{P_{input}} \times 100 \tag{3}$$

Load resistance is one of the most important parameters that play an essential role in calculating conversion efficiency. Fig. 12 describes RF-to-DC efficiency versus input power from -30 dBm to 30 dBm for various load resistors. The efficiency has been maximized at $R_L = 12\ k\Omega$. So, in the rectifier simulation, the optimum value of the resistor is set as $12\ k\Omega$. With increasing the input power from -30 dBm to 30 dBm, the conversion efficiency first increases and then decreases. Also, with the change of the load resistance in the range of input power from -15 dBm to 15 dBm, the RF to DC efficiency is more than 30%.

Fig. 13 describes RF to DC efficiency versus input power for various frequencies with the DC load $R_L = 12\ k\Omega$, representing that, the RF to DC conversion efficiency is 45% (at 1.71 GHz), 20%, (at 2.43 GHz), 4% (at 3.68 GHz), and 4% (at 6.1 GHz) at an input power of −10 dBm. The maximum value of conversion efficiency for the input power of -4 dBm at 1.71 GHz is 65.3%.

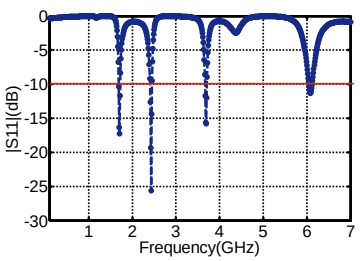



**Fig 11.** Simulated $|S_{11}|$ of the quad-band rectifier at $P_{in} = 0\ dBm$

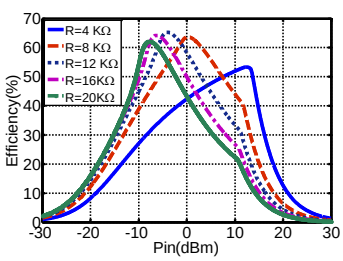



**Fig 12**. Simulated RF-to-DC conversion efficiency of the suggested rectifier versus input power with various resistive loads.

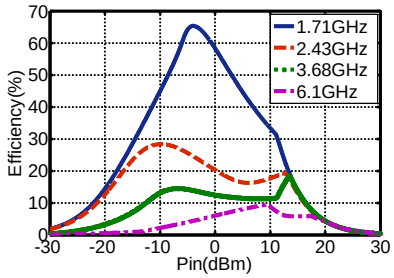
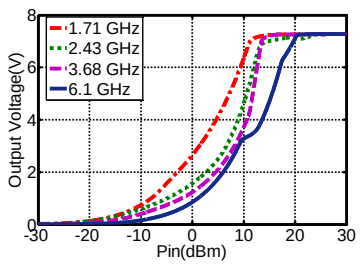
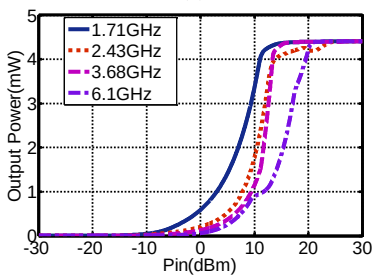



**Fig 13**. Simulated RF-to-DC conversion efficiency of the proposed rectifier versus input power at four frequencies with $R_L = 12\,K\Omega$.

Fig. 14 (a) and (b) show the output DC voltage and the output power versus the input power for various frequencies, respectively. It is found that the maximum output voltage is equal to 7.2 V in $P_{in} = 11\ dBm$ and $R_L = 12\ k\Omega$. Also, it is observed that the maximum output power is corresponded to 4.38 mW in $R_L = 12\ k\Omega$ .




(a)




(b)

**Fig 14.** (a) Simulated output voltage versus input power of the rectifier (b) Simulated output power versus input power at four frequencies with the DC load $R_L = 12\ k\Omega$.

Table 1 compares the performance of the new multiband rectifier with the parameters indicated in the published papers reporting similar projects. For a fair comparison, the simulation results of this design has been compared with the simulation results reported in the referenced papers. As indicated, the maximum RF-DC efficiency of the new rectifier happens at input powers less than 0 dBm (−4 dBm), which is lower than the factor in other related designs. Moreover, the efficiency of the new rectifier at $P_{in} = -10\ dBm$ is much higher than the reported designs.

**TABLE I**
PERFORMANCE COMPARISON OF THE SUGGESTED MULTI-BAND RECTIFIER AND OTHER REPORTED RECTIFIERS

| Ref. | Frequency (GHz) | Maximum Efficiency (%) (Simulation results) | $P_{in}$ for Max. Efficiency (dBm) (Simulation results) | Efficiency (%) at $P_{in} = -10\ dBm$ (Simulation results) |
|---|---|---|---|---|
| [15] | 1.8/2.45 | 70/58 | 10/9 | 30/13 |
| [20] | 0.95/1.835/2.45/ 2.62 | 45/30/44/25 | 10/10/10/1 0 | 26/19/14/12 |
| [21] | 1.3/1.7 2.4/3.6 | 40/41/26/ 15 | 7/4/13/7.5 | 17/15/2.5/3.5 |
| [24] | 0.9/1.8/2.4 | 9.032/30.5/8.7 | 20/18/22 | 0.2/3/0.1 |
| **This work** | **1.71/2.4/3.6/6.1** | **65.3/21/13/10** | **- 4/11/15/10** | **45/20/4/4** |

## IV. CONCLUSIONS

A rectenna having a new monopole antenna with improved bandwidth is designed and simulated. The system is equipped with a multi-band rectifier circuit to be used as an RF energy harvester. Firstly, a broadband monopole antenna with a semicircle ground plane is designed. The simulations verify that the proposed antenna has the highest bandwidth compared to the reported broadband antennas. Subsequently, a quad-band rectifier circuit has been designed using a two-stage Dickson rectifier and resonant matching network to transform the received AC signal from the antenna to a DC voltage required for powering wireless devices. The simulated results indicate that the rectenna has an RF to DC conversion efficiency of 65.3% for -4 dBm input power and a maximum DC output voltage of 7.2 V at 1.71 GHz with $R_L = 12\ k\Omega$ and $P_{in} = 11\ dBm$.

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